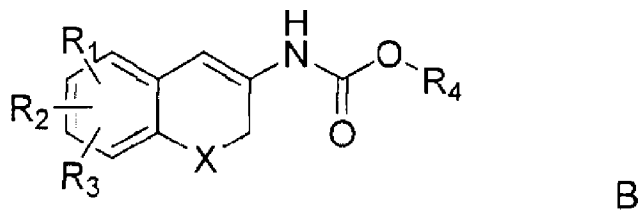
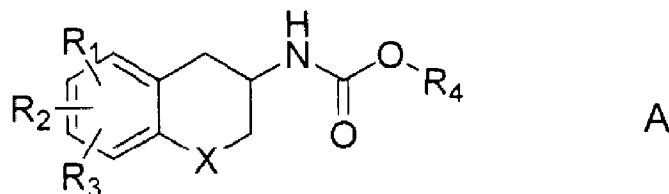




(86) **Date de dépôt PCT/PCT Filing Date:** 2007/12/12  
(87) **Date publication PCT/PCT Publication Date:** 2008/06/19  
(45) **Date de délivrance/Issue Date:** 2019/03/19  
(85) **Entrée phase nationale/National Entry:** 2009/06/08  
(86) **N° demande PCT/PCT Application No.:** GB 2007/004756  
(87) **N° publication PCT/PCT Publication No.:** 2008/071951  
(30) **Priorité/Priority:** 2006/12/12 (US60/869,605)

(51) **Cl.Int./Int.Cl.** **C07D 311/04** (2006.01),  
**C07D 405/04** (2006.01), **C07F 15/00** (2006.01)  
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(54) **Titre : PROCÉDE CATALYTIQUE POUR HYDROGENATION ASYMETRIQUE**  
(54) **Title: CATALYTIC PROCESS FOR ASYMMETRIC HYDROGENATION**



(57) **Abrégé/Abstract:**

A process for preparing the S or R enantiomer of a compound of formula A, the process comprising subjecting a compound of formula B to asymmetric hydrogenation in the presence of a chiral catalyst and a source of hydrogen, wherein: X is CH<sub>2</sub>, oxygen or sulphur; R<sub>-1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogens, halogens, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine.

## (12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
19 June 2008 (19.06.2008)

PCT

(10) International Publication Number  
**WO 2008/071951 A3**(51) International Patent Classification:  
*C07D 311/04* (2006.01) *C07F 15/00* (2006.01)  
*C07D 405/04* (2006.01)(74) Agents: CURTIS, Philip, Anthony et al.; A.A. Thornton  
& Co., 235 High Holborn, London WC1V 7LE (GB).(21) International Application Number:  
PCT/GB2007/004756(22) International Filing Date:  
12 December 2007 (12.12.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/869,605 12 December 2006 (12.12.2006) US(71) Applicant (for all designated States except US):  
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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

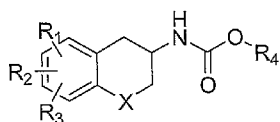
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

## Published:

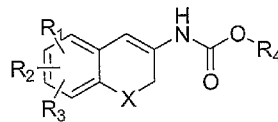
- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

(88) Date of publication of the international search report:  
2 October 2008

(54) Title: CATALYTIC PROCESS FOR ASYMMETRIC HYDROGENATION



(A)



(B)

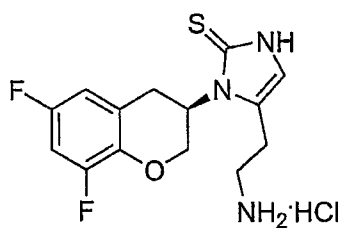
(57) Abstract: A process for preparing the S or R enantiomer of a compound of formula A, the process comprising subjecting a compound of formula B to asymmetric hydrogenation in the presence of a chiral catalyst and a source of hydrogen, wherein: X is CH<sub>2</sub>, oxygen or sulphur; R<sub>-1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogens, halogens, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine.

WO 2008/071951 A3

## CATALYTIC PROCESS FOR ASYMMETRIC HYDROGENATION

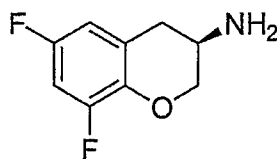
The present invention relates to an improved catalytic process for asymmetric hydrogenation. In particular, the present invention relates to a process for preparing novel intermediates useful in the synthesis of peripherally-selective inhibitors of dopamine- $\beta$ -hydroxylase, the process involving catalytic asymmetric hydrogenation. The present invention also relates to a new transition metal complex, useful in the catalytic asymmetric hydrogenation.

(R)-5-(2-Aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione hydrochloride (the compound of formula P, below) is a potent, non-toxic and peripherally selective inhibitor of D $\beta$ H, which can be used for treatment of certain cardiovascular disorders. Compound P is disclosed in WO2004/033447, along with processes for its preparation.



P

The process disclosed in WO2004/033447 involves the reaction of (R)-6,8-difluorochroman-3-ylamine hydrochloride (the structure of (R)-6,8-difluorochroman-3-ylamine is shown below as compound Q), [4-(tert-butyldimethylsilyloxy)-3-oxobutyl]carbamic acid tert-butyl ester and potassium thiocyanate.



Q

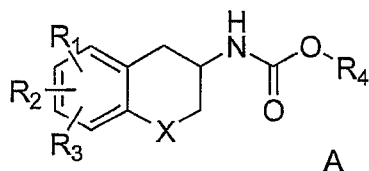
(R)-6,8-difluorochroman-3-ylamine (compound Q) is a key intermediate in the synthesis of compound P. The stereochemistry at the carbon atom to which the amine is attached gives rise to the stereochemistry of compound P, so it is advantageous that

compound Q is present in as pure a form as possible. In other words, the R enantiomer of compound Q should be in predominance, with little or no S enantiomer present. Thus, the process for preparing compound Q will advantageously produce compound Q with as high an enantiomeric excess (e.e) as possible.

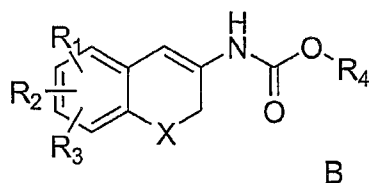
5 An advantageous process for preparing a precursor of, for example, the compound of formula Q has now been found. The process involves catalytic asymmetric hydrogenation of a corresponding novel ene-carbamate. The process may also be employed in the preparation of similar precursors useful in the production of other peripherally-selective inhibitors of dopamine- $\beta$ -hydroxylase. A new transition  
10 metal complex, which may be employed in the catalytic asymmetric hydrogenation process has also been found. The complex is particularly advantageous as it shows high activity and selectivity in the asymmetric hydrogenation reaction. Levels of activity and selectivity have also been shown to be improved when the hydrogenation is carried out in the presence of acid additives.

15 The hydrogenation of ene-carbamates using Ru-BINAP and Ru-DuPhos catalysts is described in Dupau, P.; Bruneau, C.; Dixneuf, P. H. *Tet. Asymm.* **1999**, *10*, 3467; and in Dupau, P.; Hay, A.-E.; Bruneau, C.; Dixneuf, P. H. *Tet. Asymm.* **2001**, *12*, 863. The maximum e.e's obtained with either system are up to 76 (92 for one particular substrate).

20 According to a first aspect of the present invention, there is provided a process for preparing the S or R enantiomer of a compound of formula A,



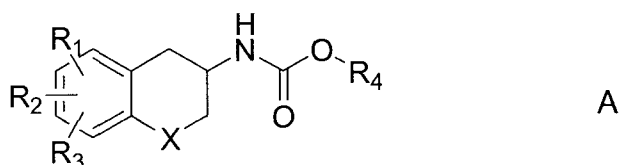
the process comprising subjecting a compound of formula B to asymmetric  
25 hydrogenation in the presence of a chiral catalyst and a source of hydrogen,



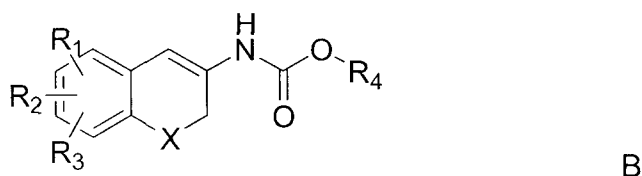
wherein: X is CH<sub>2</sub>, oxygen or sulphur; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogens, halogens, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino,

alkylamino or dialkylamino group; and  $R_4$  is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxy carbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine. Compound B may be referred to as an ene-carbamate.

According to another aspect of the present invention, there is provided a process for preparing an R or S enantiomer of a compound of formula A,



the process comprising subjecting a compound of formula B to asymmetric hydrogenation in the presence of a chiral catalyst and a source of hydrogen,

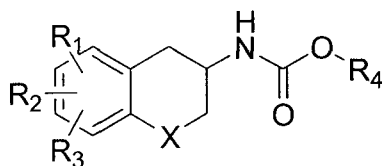


wherein: X is oxygen;  $R_1$ ,  $R_2$  and  $R_3$  are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and  $R_4$  is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxy carbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of  $R_1$ ,  $R_2$  and  $R_3$  is fluorine.

According to another aspect of the present invention, there is provided a compound of formula A, the compound being in the form of the  $\geq 95$  % pure

3a

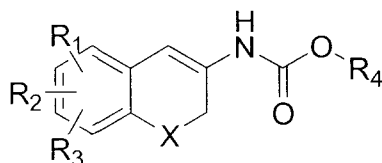
R enantiomer, or the  $\geq 95$  % pure S enantiomer,



A

- 5 wherein wherein: X is oxygen;  $R_1$ ,  $R_2$  and  $R_3$  are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and  $R_4$  is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, 10 alkoxy carbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of  $R_1$ ,  $R_2$  and  $R_3$  is fluorine.

- According to a further aspect of the present invention, there is provided 15 a compound of formula B

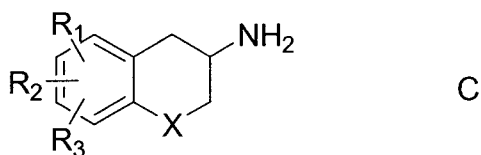


B

- wherein: X is oxygen;  $R_1$ ,  $R_2$  and  $R_3$  are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, 20 alkylamino or dialkylamino group; and  $R_4$  is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and 25 the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of  $R_1$ ,  $R_2$  and  $R_3$  is fluorine.

3b

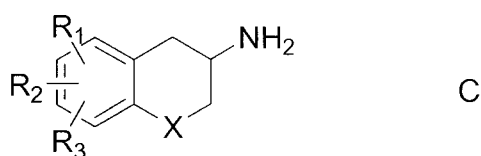
According to another aspect of the present invention, there is provided L-tartrate salt of an R or S enantiomer of a compound of formula C



wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and  
 5 signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group,  
 10 optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

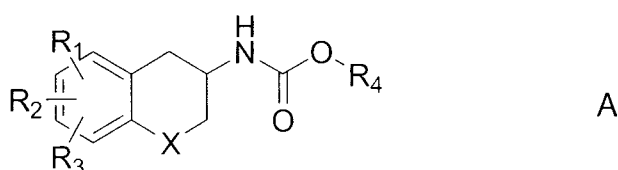
According to a further aspect of the present invention, there is provided a transition metal complex having the formula [((R)-(+)-2,2',6,6'-tetramethoxy-  
 15 4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)RuCl<sub>2</sub>(dmf)<sub>2</sub>].

According to another aspect, there is provided a process for preparing an R or S enantiomer of a compound of formula C,



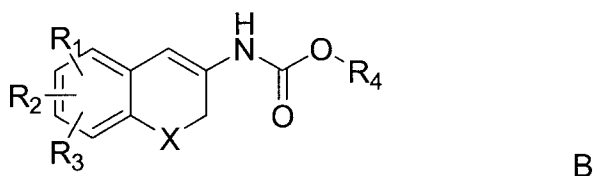
Comprising:

- 20 (i) forming an R or S enantiomer of a compound of formula A by a process described herein,



3c

the process for preparing the R or S enantiomer of a compound of formula A comprising subjecting a compound of formula B to asymmetric hydrogenation in the presence of a chiral catalyst and a source of hydrogen,

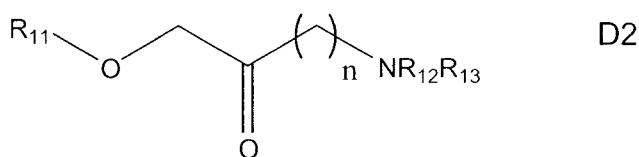


5

- (ii) converting the R or S enantiomer of the compound A to the respective R or S enantiomer of a compound of formula C, wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and
- 10 wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and
- 15 wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

According to another aspect, there is provided a process, wherein the compound A is converted to compound C by a reaction involving substituting the group -C(=O)-O-R<sub>4</sub> with H.

- According to another aspect, there is provided a process described
- 20 herein, comprising reacting the R or S enantiomer of the compound of formula C with a compound of formula D2

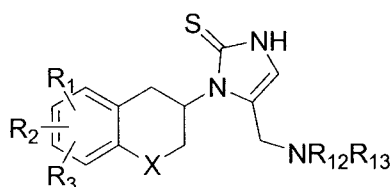
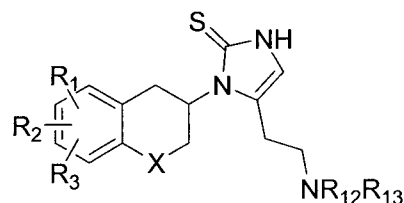
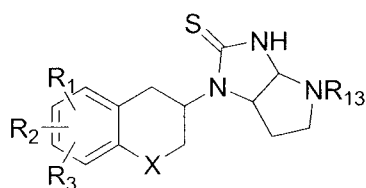
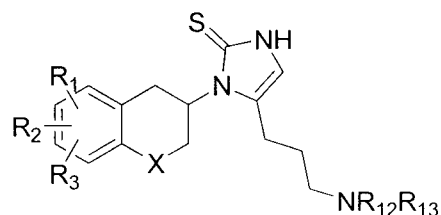


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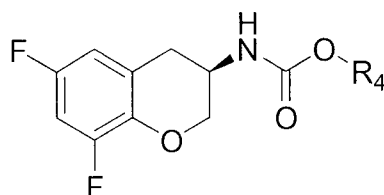
3d

where n signifies 1, 2 or 3; when n is 1 or 2, R<sub>12</sub> signifies hydrogen, alkyl or alkylaryl group; R<sub>11</sub> signifies a hydroxyl protecting group and R<sub>13</sub> signifies an amino protecting group; when n signifies 3, R<sub>11</sub> signifies a hydroxyl protecting group but R<sub>12</sub> and R<sub>13</sub> taken together represent a phthalimido group; and with  
 5 a water soluble thiocyanate salt in the presence of an organic acid in a substantially inert solvent, followed by subsequent deprotection of the intermediate products F to I:

**F****G****H****I**

10 Throughout the specification, unless stated otherwise, the terms 'alkoxy' and 'alkyloxy' are equivalent.

In an embodiment, X is O. In another embodiment, at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine. Suitably, compound A has the following formula:



3e

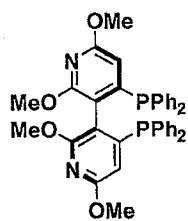
In an embodiment,  $R_4$  is  $C_1$  to  $C_4$  alkyl. Optionally,  $R_4$  is methyl (i.e. the methyl-substituted ene-carbamate), ethyl (i.e. the ethyl-substituted ene-carbamate) or tBu (i.e. the tBu-substituted ene-carbamate). Preferably,  $R_4$  is methyl. In an alternative embodiment,  $R_4$  is benzyl (i.e. the benzyl-substituted  
 5 ene-carbamate).

The chiral catalyst may comprise a transition metal complex comprising a chiral ligand. Suitably, the catalyst has the formula  
 $[(\text{bisphosphine})\text{Ru}(\text{arene})\text{X}']\text{Y}$ ,  $[(\text{bisphosphine})\text{Ru}(\text{L})_2]$  or  
 $[(\text{bisphosphine})\text{Ru}(\text{L}')_2\text{X}'_2]$ , wherein the bisphosphine is chiral,  $\text{X}'$  is a singly-  
 10 negative monodentate ligand,  $\text{Y}$  is a balancing anion,  $\text{L}$  is a monovalent negative coordinating ligand and  $\text{L}'$  is a non-ionic monodentate ligand.

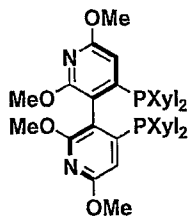
Examples of the bisphosphine ligands that can be used in the asymmetric hydrogenation of the present invention are shown in Scheme 1 below. Bisphosphine ligands having the opposite stereochemistry to that of  
 15 the ligands in scheme 1 may also be used in the asymmetric hydrogenation of the present invention.

### Scheme 1

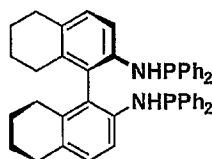
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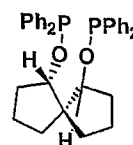
P-Phos



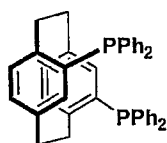
Xyl-P-Phos



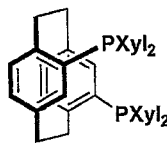
H8-BINAMP



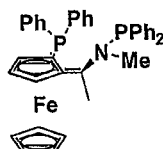
SpirOP



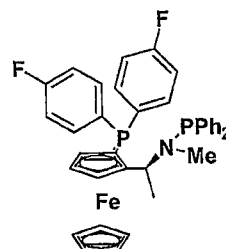
Phanephos



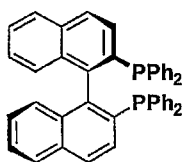
Xyl-Phanephos



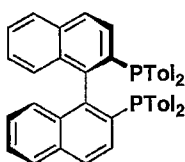
MeBoPhoz



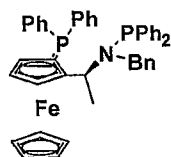
(p-FPh)MeBoPhoz



BINAP



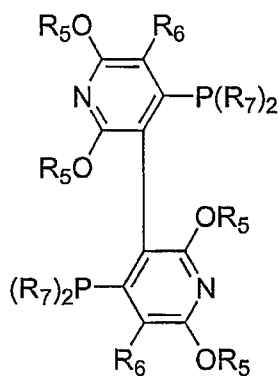
Tol-BINAP



BnBoPhoz

In an embodiment, the bisphosphine may be the R or S enantiomer of BINAP or TolBINAP. Alternatively, the bisphosphine may be the R or S enantiomer of a compound having the following formula

5



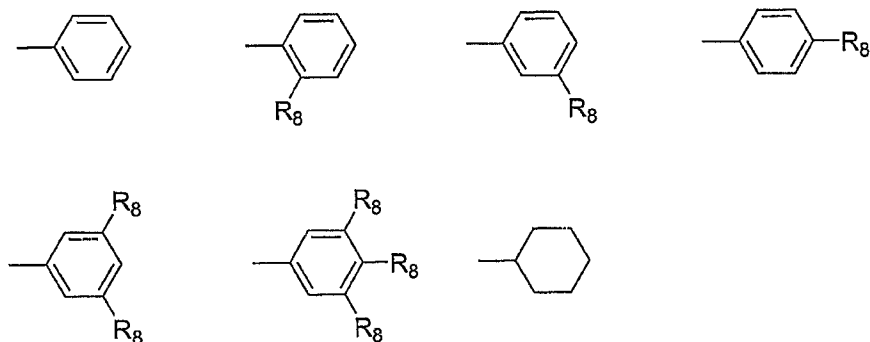
wherein  $R_5$  is hydrogen or alkyl;  $R_6$  is hydrogen, halogen, alkyl, alkoxy, hydroxy, chiral hydroxyalkyl, amino, mono- and di-alkylamino, vinyl or allyl; and  $R_7$  is chosen from the following groups:

10

WO 2008/071951

PCT/GB2007/004756

5



wherein  $R_8$  is alkyl, alkoxy or amino, and, where there is more than one group  $R_8$ , each  $R_8$  may be the same or different from the others; or the group  $P(R_8)_2$ , may form a group chosen from the following:

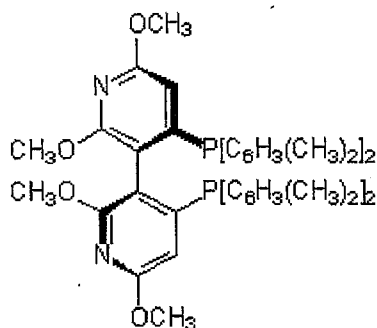


5

wherein  $R_9$  is alkyl.

In an embodiment, the bisphosphine is (S)- or (R)-PPhos.

Preferably, the bisphosphine is (S)-(-)- or (R)-(+)-2,2',6,6'-tetramethoxy-4,4'-  
10 bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine of the following formula



Suitably, the bisphosphine is ((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-  
15 xylyl)phosphino)-3,3'-bipyridine).

In an embodiment,  $X'$  is chloride. In another embodiment,  $Y$  is chloride. Both  $X'$  and  $Y$  may be chloride. In another embodiment, arene is p-cymene or benzene. One

particular catalyst of interest is [RuCl(R)-TolBINAP(*p*-cymene)]Cl, which can be formed from (R)-TolBINAP (CA RN 99646-28-3) and dichloro-(*p*-cymene)-ruthenium (II) dimer (CA RN 52462-29-0).

Preferably, L is acac. Suitably, L' is dmf. Other options for the ligand include acetyl,  
5 trifluoroacetyl, tetrafluoroborate, and mono- and diamines.

Most preferably, the complex has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)Ru(acac)<sub>2</sub>]. Alternatively, the complex has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)RuCl<sub>2</sub>(dmf)<sub>2</sub>].

10 In an embodiment, the hydrogenation is carried out in the presence of an acid. Optionally, the acid is HBF<sub>4</sub>, HCl, HBr, CF<sub>3</sub>SO<sub>3</sub>H, CH<sub>3</sub>COOH or H<sub>3</sub>PO<sub>4</sub>. Preferably, the acid is H<sub>3</sub>PO<sub>4</sub>.

In an embodiment, the acid is present in a solvent. For example, the acid solvent is diethyl ether or water.

15 In an embodiment, the compound B/acid molar ratio ranges from 3.5/1 to 4/1. Suitably, the compound B/acid molar ratio ranges from 3.8/1 to 4/1. Preferably, the compound B/acid molar ratio ranges from 3.9/1 to 4/1. More preferably, the compound B/acid molar ratio is 4/1.

In another embodiment, the compound B/catalyst molar ratio ranges from 100/1  
20 to 1000/1. Suitably, the compound B/catalyst molar ratio ranges from 250/1 to 1000/1. Preferably, the compound B/catalyst molar ratio ranges from 500/1 to 1000/1. More preferably, the compound B/catalyst molar ratio ranges from 750/1 to 1000/1. Most preferably, the compound B/catalyst molar ratio is 1000/1.

The hydrogenation may be carried out in the presence of a solvent. For  
25 example, the hydrogenation solvent is selected from a substituted or unsubstituted straight- or branched-chain C<sub>1</sub> to C<sub>6</sub> alcohol, an arene or mixtures thereof. Optionally, the solvent is selected from MeOH, EtOH, <sup>i</sup>PrOH, 1-PrOH, 1-BuOH, 2-BuOH, CF<sub>3</sub>CH<sub>2</sub>OH, DCM (dichloromethane), DCE (dichloroethane), THF (tetrahydrofuran), toluene or a 1:1 mixture of MeOH and DCM.

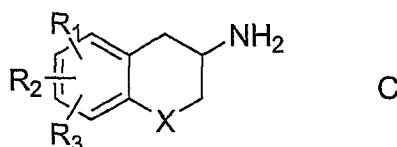
30 The hydrogenation may be carried out at a temperature ranging from 30°C to 70°C. Suitably, the hydrogenation is carried out at a temperature ranging from 40°C to 60°C. Preferably, the hydrogenation is carried out at a temperature ranging from 50°C to 60°C. More preferably, the hydrogenation is carried out at a temperature of 60°C.

The hydrogenation may be carried out at a pressure ranging from 10 bars to 30 bars. Suitably, the hydrogenation is carried out at a pressure ranging from 20 bars to 30 bars. Preferably, the hydrogenation is carried out at a pressure of 30 bars.

In a further embodiment, the process further comprises subsequently  
5 recrystallising the compound of formula A. Optionally, the recrystallisation is carried out in DCM/hexane.

In an embodiment, compound A is in the form of the S enantiomer. In an alternative embodiment, compound A is in the form of the R enantiomer.

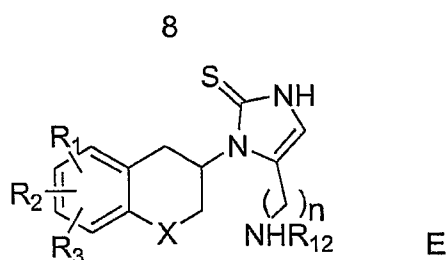
In a still further embodiment, the process further comprises converting the R or S  
10 enantiomer of compound A to the respective R or S enantiomer of a compound of formula C, or a salt thereof.



15 For example, the R or S enantiomer of compound A is converted to the respective R or S enantiomer of the compound of formula C by hydrolysis. Hydrolysis may be carried out using 40% potassium hydroxide in methanol, followed by isolation of the crude amine and crystallisation of the amine as a salt with L-tartaric acid.

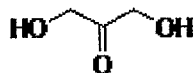
Alternative methods of converting compound A to C are possible, depending on  
20 the nature of R<sub>4</sub>. For example, the following processes may be used: mild acidic cleavage (in the presence of, for example, trifluoroacetic acid, HCl/EtOAc, or HBr/AcOH), acidic hydrolysis (strong aqueous acid with or without solvent), catalytic hydrogenolysis (Pd/C with a hydrogen source), etc. A comprehensive list of carbamates and methods for their cleavage can be found, for example, in Protective Groups in  
25 Organic Synthesis / Theodora W. Green and Peter G. M. Wuts, 2<sup>nd</sup> ed., Wiley-Interscience 1991, p. 315-348.

In a yet further embodiment, the process further comprises reacting the R or S enantiomer of the compound of formula C, or a salt thereof, to produce the respective R or S enantiomer of a compound of formula E or a salt thereof.



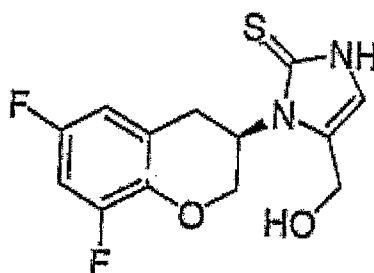
In broad terms, the compound C can be converted to the compound E by using the compound C as an amino component to build the N(1) moiety of the substituted 5 imidazole-2-thione ring of compound E. More specifically, the amino group on the compound C may be converted to a 5-substituted imidazole-2-thione ring, and the group substituted at the 5 position may be converted to the group  $-(CH_2)_n-NHR_{12}$ .

In one embodiment, the R or S enantiomer of the compound of formula C, or a salt thereof, is reacted with a compound of formula D1



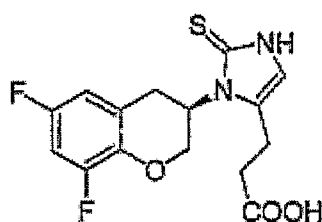
D1

to form a compound of formula D3



D3

followed by reaction of D3 with a dialkyl malonate and a base in the presence of a solvent, to form a compound of formula D4



D4

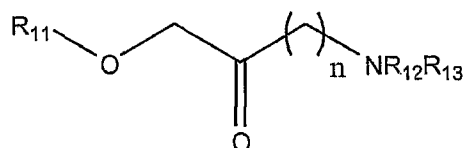
followed by reaction of D4 with a suitable azide in the presence of a solvent, and then reaction with hydrochloric acid to form a compound of formula E.

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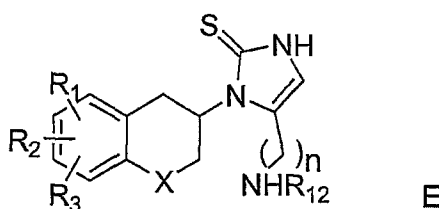
In a further embodiment, the R or S enantiomer of the compound of formula C is reacted with a compound of formula D2



D2

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to produce the respective R or S enantiomer of a compound of formula E or a salt thereof

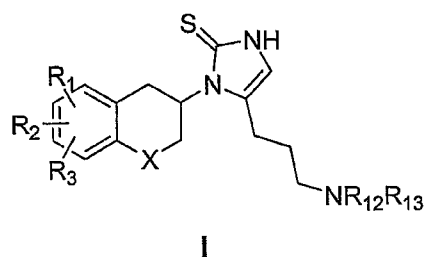
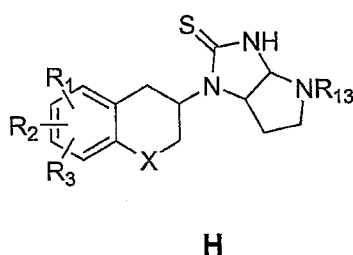
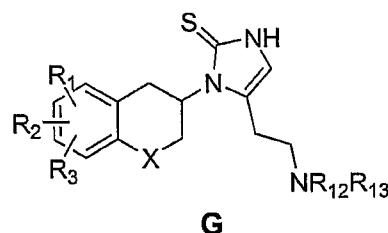
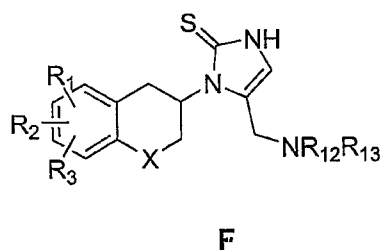


E

- 10 where n signifies 1, 2 or 3; R<sub>12</sub> signifies hydrogen, alkyl or alkylaryl group, R<sub>11</sub> signifies a hydroxyl protecting group and R<sub>13</sub> signifies an amino protecting group, or R<sub>11</sub> is defined as above but R<sub>12</sub> and R<sub>13</sub> taken together represent a phthalimido group; with a water soluble thiocyanate salt in the presence of an organic acid in a substantially inert solvent, followed by subsequent deprotection of the intermediate products F to I:



10



Preferably, the water soluble thiocyanate salt is an alkali metal thiocyanate salt or a tetraalkylammonium thiocyanate salt. Preferably the solvent is an organic solvent.

- 5 In an embodiment, X is O. In another embodiment, n is 2 or 3. Preferably X is O and n is 2 or 3. In a further embodiment, at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine. Optionally, the product of the reaction of the R or S enantiomer of the compound of formula C and the compound of formula D is (S)-5-(2-aminoethyl)-1-(1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (S)-5-(2-aminoethyl)-1-(5,7-difluoro-1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-chroman-3-yl-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(8-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(8-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(8-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6,7-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (S)-5-(2-aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (R)-5-(2-aminoethyl)-1-(6,7,8-
- 10
- 15
- 20

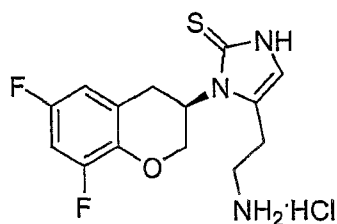
trifluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-chloro-8-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-methoxy-8-chlorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-nitrochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(8-nitrochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-[6-(acetylamino)chroman-3-yl]-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-chroman-3-yl-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-hydroxy-7-benzylchroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(3-aminopropyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*S*)-5-(3-aminopropyl)-1-(5,7-difluoro-1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (*R,S*)-5-(2-aminoethyl)-1-(6-hydroxythiochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R,S*)-5-(2-aminoethyl)-1-(6-methoxythiochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-benzylaminoethyl)-1-(6-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-benzylaminoethyl)-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-1-(6-hydroxychroman-3-yl)-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione; (*R*)-1-(6,8-difluorochroman-3-yl)-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione or (*R*)-1-chroman-3-yl-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione.

20

The product of the reaction of the *R* or *S* enantiomer of the compound of formula C and the compound of formula D may also be a salt of (*S*)-5-(2-aminoethyl)-1-(1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (*S*)-5-(2-aminoethyl)-1-(5,7-difluoro-1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-chroman-3-yl-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(8-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(8-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(8-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6,7-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*S*)-5-(2-aminoethyl)-1-(6,8-

- difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6,7,8-trifluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-chloro-8-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-methoxy-8-chlorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-  
 5 (6-nitrochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(8-nitrochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-[6-(acetylamino)chroman-3-yl]-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-chroman-3-yl-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-aminoethyl)-1-(6-hydroxy-7-  
 10 benzylchroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-aminomethyl-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(3-aminopropyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*S*)-5-(3-aminopropyl)-1-(5,7-difluoro-1,2,3,4-tetrahydronaphthalen-2-yl)-1,3-dihydroimidazole-2-thione; (*R,S*)-5-(2-aminoethyl)-1-(6-hydroxythiochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R,S*)-5-(2-  
 15 aminoethyl)-1-(6-methoxythiochroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-benzylaminoethyl)-1-(6-methoxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-5-(2-benzylaminoethyl)-1-(6-hydroxychroman-3-yl)-1,3-dihydroimidazole-2-thione; (*R*)-1-(6-hydroxychroman-3-yl)-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione; (*R*)-1-(6,8-difluorochroman-3-yl)-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione or  
 20 (*R*)-1-chroman-3-yl-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione. Preferably the salt is the hydrochloride salt.

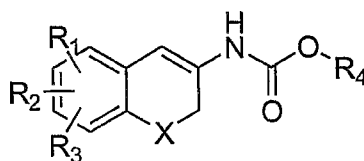
Alternatively, the product of the reaction of the *R* or *S* enantiomer of the compound of formula C and the compound of formula D is the respective *R* or *S* enantiomer of the  
 25 compound of formula P.



P

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According to a second aspect of the present invention, there is provided a compound of formula B

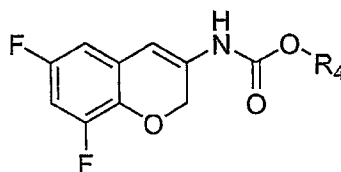


B

5 wherein: X is CH<sub>2</sub>, oxygen or sulphur; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogens, halogens, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxycarbonyl  
10 groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine.

In one embodiment, X is O. In another embodiment, at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine. Suitably, compound B has the following formula:

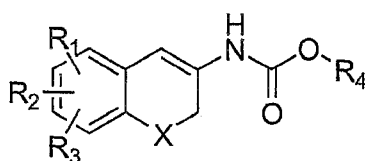
15



In an embodiment, R<sub>4</sub> is C<sub>1</sub> to C<sub>4</sub> alkyl. Optionally, R<sub>4</sub> is methyl (i.e. the methyl-substituted ene-carbamate), ethyl (i.e. the ethyl-substituted ene-carbamate) or tBu (i.e.  
20 the tBu-substituted ene-carbamate). Preferably, R<sub>4</sub> is methyl. In an alternative embodiment, R<sub>4</sub> is benzyl (i.e. the benzyl-substituted ene-carbamate).

According to another aspect of the present invention, there is provided the use of a chiral catalyst comprising a transition metal complex comprising a chiral ligand in the asymmetric hydrogenation of a compound of formula B,

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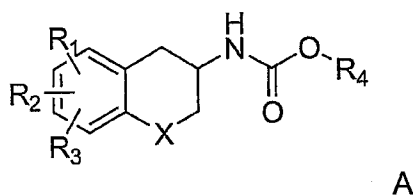


B

wherein compound B is as described above.

The catalyst may have the formula  $[(\text{bisphosphine})\text{Ru}(\text{arene})\text{X}']\text{Y}$ ,  $[(\text{bisphosphine})\text{Ru}(\text{L})_2]$  or  $[(\text{bisphosphine})\text{Ru}(\text{L}')_2\text{X}'_2]$ , as described above.

- 5 According to a further aspect of the present invention, there is provided a compound of formula A, the compound being in the form of the substantially pure R enantiomer, the substantially pure S enantiomer, or a mixture of the R and S enantiomers

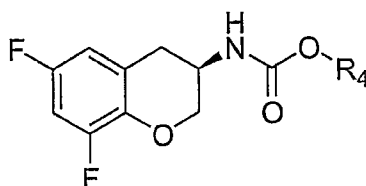


10

wherein X, R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub> and R<sub>4</sub> have the same meanings as defined above.

As used herein, the term "substantially pure" refers to a percentage purity of at least 95%, preferably at least 98%, more preferably at least 99%, most preferably 100%. Substantially pure can be defined as  $\geq 95\%$  pure.

- 15 In an embodiment, X is O. In another embodiment, at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine. Optionally, compound A has the following formula:

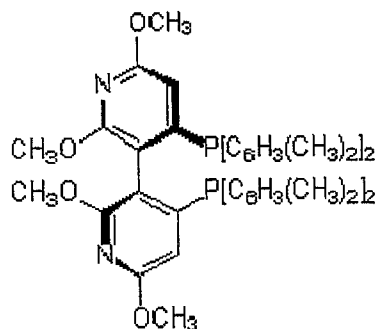


- In an embodiment, R<sub>4</sub> is C<sub>1</sub> to C<sub>4</sub> alkyl. Optionally, R<sub>4</sub> is methyl, ethyl or <sup>t</sup>Bu.  
 20 Preferably, R<sub>4</sub> is methyl. In an alternative embodiment, R<sub>4</sub> is benzyl.

In an embodiment, compound A is in the form of the R enantiomer. In an alternative embodiment, compound A is in the form of the S enantiomer. In a further embodiment, compound A is in the form of a mixture of the R and S enantiomers. Optionally, the mixture is a racemic mixture.

- 25 According to a further aspect of the present invention, there is provided a transition metal complex comprising a ligand of (R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine (compound J):

15



J

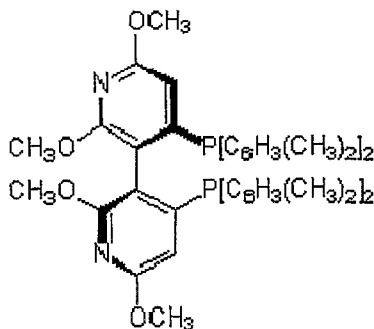
In an embodiment, the complex has the formula  $[(R)-(+)-2,2',6,6'-\text{tetramethoxy-4,4'-bis}(\text{di}(3,5\text{-xylyl})\text{phosphino})-3,3'\text{-bipyridine})\text{Ru}(\text{arene})\text{X}'\text{Y}]$ ,  $[(R)-(+)-2,2',6,6'$   
 5  $\text{tetramethoxy-4,4'-bis}(\text{di}(3,5\text{-xylyl})\text{phosphino})-3,3'\text{-bipyridine})\text{Ru}(\text{L})_2]$  or  $[(R)-(+)-2,2',6,6'$   
 $\text{tetramethoxy-4,4'-bis}(\text{di}(3,5\text{-xylyl})\text{phosphino})-3,3'\text{-bipyridine})\text{Ru}(\text{L}')_2\text{X}'_2]$ ,  
 wherein  $\text{X}'$  is a singly-negative monodentate ligand,  $\text{Y}$  is a balancing anion,  $\text{L}$  is a doubly-negative bidentate ligand and  $\text{L}'$  is a non-ionic monodentate ligand.

In an embodiment,  $\text{X}'$  is chloride. In another embodiment  $\text{Y}$  is chloride. Both  $\text{X}'$   
 10 and  $\text{Y}$  may be chloride. In another embodiment, arene is p-cymene or benzene. In a further embodiment,  $\text{L}$  is acac. Optionally,  $\text{L}'$  is dmf. Other options for the ligand include acetyl, trifluoroacetyl, tetrafluoroborate, and mono- and diamines.

In a further embodiment, the complex has the formula  $[(R)-(+)-2,2',6,6'$   
 $\text{tetramethoxy-4,4'-bis}(\text{di}(3,5\text{-xylyl})\text{phosphino})-3,3'\text{-bipyridine})\text{RuCl}_2(\text{dmf})_2]$ .

15 In an embodiment, the complex is suitable for use as a catalyst.

According to a further aspect of the present invention, there is provided  $(R)-(+)-2,2',6,6'$   
 $\text{tetramethoxy-4,4'-bis}(\text{di}(3,5\text{-xylyl})\text{phosphino})-3,3'\text{-bipyridine}$  (compound D):



J

Ru-catalysed hydrogenation investigations have revealed that full conversion and e.e.'s up to 90% were obtained using the methyl- and ethyl-substituted ene-carbamate in the presence of Ru(Xyl-P-Phos)-based catalysts.

The reactivity and enantioselectivity in the asymmetric hydrogenation of the ene carbamate substrates has been found to vary in the order OBn < O<sup>t</sup>Bu < OEt < OMe.

The methyl-substituted ene-carbamate exhibited similar conversions and e.e.'s to the ethyl-substituted ene-carbamate, although the methyl-substituted ene-carbamate was found to be slightly more reactive than the ethyl-substituted ene-carbamate. Furthermore, on recrystallisation of the hydrogenated product, a higher enantiopurity upgrade was found for products produced from methyl-substituted ene-carbamate hydrogenation than ethyl-substituted ene-carbamate hydrogenation. Thus, the methyl-substituted ene-carbamate may be preferred over the ethyl-substituted ene-carbamate because of the combination of good activity, selectivity and the ease of enantiopurity upgrade by recrystallisation.

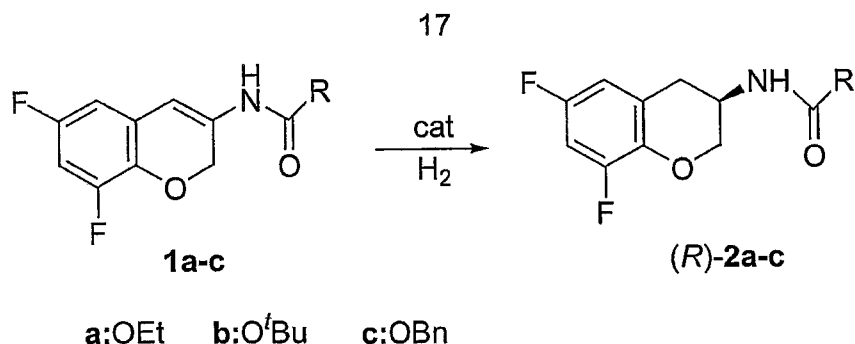
Asymmetric hydrogenation using a rhodium-based catalyst has also been investigated. In particular, [Rh-(bisphosphine)(L)]X<sup>+</sup> cationic complexes (where L = cyclooctadiene, and X<sup>+</sup> = BF<sub>4</sub>, OTf) have been investigated. Rh-bisphosphine catalysed hydrogenation revealed moderate to high activity and low enantioselectivity for the ene-carbamate substrates.

The invention will now be described with reference to the following examples.

### Experimental Examples

An investigation of the effect of the catalyst on the enantioselective hydrogenation of the prochiral ene-carbamates 1a-c (as shown in Scheme 2 below) was carried out using ruthenium-bisphosphine-based catalysts (Tables 1 to 4) and rhodium-bisphosphine-based catalysts (Table 5). Initial tests were performed in MeOH at a substrate to catalyst molar ratio (S/C) of 100/1, under 30bar H<sub>2</sub> pressure. The reactions were run in an 8-well parallel pressure hydrogenator Argonaut Endeavour.

### Scheme 2



where R = a, b, or c, accordingly.

### ***Ruthenium-bisphosphine Catalysis***

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In the case of  $\text{RuCl}_2(\text{Ar-P-Phos})(\text{dmf})_2$  catalysts, the activity was substrate dependent and varied as follows:  $\text{OEt} \approx {}^t\text{Bu} > \text{OBn}$  (Table 1, entry 1, Table 2, entry 1, and Table 3, entry 1. The enantioselectivity was observed to be substrate dependent, with the ethyl substituted ene-carbamate 1a resulting in the highest e.e (Table 1, entry 10 4, Table 2, entry 4, and Table 3, entry 3).

Generally ruthenium-Arene-P-Phos catalysts bearing chloride anionic ligands were found to be most selective (Table 1, entry 1, Table 2, entry 4, and Table 3, entry 3).

One particular catalyst,  $\text{Ru}(R\text{-Xyl-P-Phos})(\text{acac})_2$  gave full conversion and 90% 15 e.e when the ethyl ene carbamate 1a was employed.

HPLC conversion and enantioselectivity for substrate 1b was not determined in some cases, since the substrate 1b and the *R*-carbamate overlap. Attempts to optimise the HPLC methods lead to no change in the area ratio of (1b+(*R*)-2b) to (*S*)-2b. An accurate enantioselectivity determination in the case of this substrate is currently 20 possible only when the reaction reaches full conversion (e.g. Table 2, entries 1 and 4, when the enantioselectivity values at 254 and 210nm are consistent).

In some instances, a byproduct eluting at approximately 3 min was observed. While this byproduct has not yet been identified, it could be the result of either poor stability of these ene-carbamates in solution under prolonged reaction time or of their 25 reaction with the alcoholic solvent.

$\text{Ru}(\text{COD})(\text{bismethylallyl})_2$  and  $\text{Ru}(\text{COD})(\text{CF}_3\text{COO})_2$  (COD =  $\eta$ -1,5-cyclooctadiene) precursors in combination with bisphosphine ligands have been tested



in the hydrogenation of substrate 1a. Generally, the activity and selectivity of the catalysts generated from these ruthenium precursors was found to be low (Table 4).

**Table 1.** Asymmetric hydrogenation of **1a** using Ru-bisphosphine-based catalysts.<sup>a</sup>

Entry	Catalyst	Conv (%) ( <sup>1</sup> HNMR) <sup>c</sup>	Conv (%) (HPLC, 254nm)	Conv (%) (HPLC, 210nm)	e.e. (%) <sup>b</sup> (210nm)
1	RuCl <sub>2</sub> -( <i>R</i> )-P-Phos-(dmf) <sub>2</sub>	>99	90	98	81( <i>R</i> )
2	RuCl <sub>2</sub> -( <i>S</i> )-P-Phos-(dmf) <sub>2</sub>	49	10	31	36( <i>S</i> )
3	RuCl <sub>2</sub> -( <i>R</i> )-MeBoPhoz-(dmf) <sub>2</sub>	12	10	15	83( <i>R</i> )
4	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	99	>99	>99	88( <i>R</i> )
5	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-Phane-Phos-(dmf) <sub>2</sub>	NA	21	48	13 ( <i>S</i> )
6	RuCl <sub>2</sub> -( <i>R</i> )-Phane-Phos-(dmf) <sub>2</sub>	NA	8	26	<5
7	[RuCl( <i>S</i> )-P-Phos( <i>p</i> -cym)]Cl	33	7	16	73( <i>S</i> )
8	[RuCl( <i>S</i> )-P-Phos(benzene)]Cl	92	60	86	71( <i>S</i> )
9	[RuCl( <i>R</i> )-Xyl-P-Phos( <i>p</i> -cym)]Cl	38	8	20	74( <i>R</i> )
10	[RuCl( <i>R</i> )-ToI BINAP( <i>p</i> -cym)]Cl	80	33	66	85 ( <i>R</i> )
11	[RuCl( <i>S</i> )-BINAP( <i>p</i> -cym)]Cl	77	28	63	84( <i>S</i> )
12	RuCl( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	>99	>99	>99	90( <i>R</i> )

13	RuCl(S)-P- Phos(acac) <sub>2</sub>	82	31	67	83(S)
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a) Reaction conditions: 0.3mmol 1a, 0.003mmol catalyst (S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD column, 70% MeOH:30% IPA, 0.5mL/min. c) NA = not available

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**Table 2.** Asymmetric hydrogenation of **1b** using Ru-bisphosphine-based catalysts.<sup>a</sup>

Entry	Catalyst	Conv (%) ( <sup>1</sup> HNMR)	e.e. (%) <sup>b,c</sup>
1	RuCl <sub>2</sub> -( <i>R</i> )-P-Phos-(dmf) <sub>2</sub>	>99	81 ( <i>R</i> )
2	RuI <sub>2</sub> -( <i>S</i> )-P-Phos-(dmf) <sub>2</sub>	47	ND
3	RuCl <sub>2</sub> -( <i>R</i> )-MeBoPhoz-(dmf) <sub>2</sub>	58	ND
4	RuCl <sub>2</sub> -( <i>S</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	>99	80 ( <i>S</i> )
5	[RuCl( <i>S</i> )-P-Phos( <i>p</i> -cym)]Cl	41	ND
6	[RuCl( <i>S</i> )-P- Phos(benzene)]Cl	92	ND
7	[RuCl( <i>R</i> )-Xyl-P-Phos( <i>p</i> - cym)]Cl	73	ND
8	[RuCl( <i>R</i> )-TolBINAP( <i>p</i> - cym)]Cl	94	ND
9	[RuCl( <i>S</i> )-BINAP( <i>p</i> -cym)]Cl	90	ND
10	RuCl( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	<5	ND

a) Reaction conditions: 0.3mmol substrate, 0.003mmol catalyst (S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD column, 70% MeOH:30% IPA, 0.5mL/min. c) ND = not determined.

**Table 3.** Asymmetric hydrogenation of **1c** using Ru-bisphosphine-based catalysts.<sup>a</sup>

Entry	Catalyst	Conv (%) ( <sup>1</sup> HNMR)	Conv (%) (HPLC,254nm)	Conv (%) (HPLC,210 nm)	e.e. (%) <sup>b</sup> (210nm)
1	RuCl <sub>2</sub> -(S)-P- Phos-(dmf) <sub>2</sub>	NA <sup>c</sup>	<10	38	46(S)
2	RuCl <sub>2</sub> -(S)- MeBoPhoz- (dmf) <sub>2</sub>	<5	5	5	0
3	RuCl <sub>2</sub> -(R)-Xyl-P- Phos-(dmf) <sub>2</sub>	93	36	73	73 (R)

a) Reaction conditions: 0.3mmol substrate, 0.003mmol catalyst (S/C=100/1),  
 5 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined  
 using Diacel ChiralPak AD column, 70% MeOH:30% IPA, 0.5mL/min. c) NA = not  
 available.

**Table 4.** Asymmetric hydrogenation of **1a** using *in situ* Ru-bisphosphine-based  
 10 catalysts.<sup>a</sup>

Entry	Ru precursor/ ligand	Conv (%) (HPLC, 254nm)	Conv (%) (HPLC, 210nm)	e.e. (%) <sup>b</sup> (210nm)
1	Ru(COD)(bismethylallyl) <sub>2</sub> /(R)- Xyl-P-Phos	12	41	34(R)
2	Ru(COD)(bismethylallyl) <sub>2</sub> /(R)- MeBoPhoz	<5	<5	-
3	Ru(COD)(bismethylallyl) <sub>2</sub> / (R)-Xyl-Phane-Phos	24	59	9(S)
4	Ru(COD)(CF <sub>3</sub> COO) <sub>2</sub> /(R)- MeBoPhoz	6	20	<5

5	Ru(COD)(CF <sub>3</sub> COO) <sub>2</sub> /( <i>R</i> )-Xyl-Phane-Phos	10	37	<5
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a) Reaction conditions: 0.3mmol **1a**, 0.003mmol catalyst ruthenium precursor, 0.0036mmol ligand stirred in 1mL MeOH at 60°C for 0.5hrs(S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimized reaction time 20hrs. b) e.e. was determined using Diacel 5 ChiralPak AD column, 70% MeOH:30% IPA, 0.5mL/min.

### ***Rhodium-bisphosphine Catalysis***

Hydrogenation of ene-carbamates **1a-c** using catalysts of general formula  
 10 [Rh(bisphosphine)(COD)]X (X = BF<sub>4</sub>, OTf), where bisphosphine is Xyl-P-Phos, P-Phos, Xyl-PhanePhos, PhanePhos, MeBophoz, Spiro-P, H8-BINAM-P in methanol at S/C 100, 60°C, 30 bar H<sub>2</sub> led to low enantioselectivities (Table 5).

**Table 5.** Asymmetric hydrogenation using Rh-bisphosphine-based catalysts.<sup>a</sup>

Entry	Ru precursor/ ligand	substrate	Conv (%) (HPLC, 254nm)	Conv (%) (HPLC, 210nm)	e.e. (%) <sup>b</sup> (210nm)
1	[Rh(COD)( <i>R</i> -BINAM-P)]BF <sub>4</sub>	<b>1a</b>	9	35	<5
2	[Rh(COD)( <i>R</i> -BINAM-P)]BF <sub>4</sub>	<b>1b</b>	ND	ND	ND
3	[Rh(COD)( <i>R</i> -BINAM-P)]BF <sub>4</sub>	<b>1c</b>	37	77	<5
4	[Rh(COD)( <i>R</i> -Spiro-P)]BF <sub>4</sub>	<b>1a</b>	95	98	<5
5	[Rh(COD)( <i>R</i> -Spiro-P)]BF <sub>4</sub>	<b>1b</b>	>99	>99	<5
6	[Rh(COD)( <i>R</i> -Spiro-P)]BF <sub>4</sub>	<b>1c</b>	>99	>99	<5
7	[Rh(COD)( <i>R</i> -Phane-Phos)]BF <sub>4</sub>	<b>1a</b>	>99	>99	<5
8	[Rh(COD)( <i>R</i> -Phane-Phos)]BF <sub>4</sub>	<b>1c</b>	>99	>99	<5

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9	[Rh(COD) <sub>2</sub> ]OTf/( <i>R</i> )- MeBoPhoz	<b>1a</b>	17	49	40 (S)
10	[Rh(COD) <sub>2</sub> ]OTf/ 4-F-Ph-( <i>R</i> )-MeBoPhoz	<b>1a</b>	<5	<5	<5
11	[Rh(COD) <sub>2</sub> ]OTf/( <i>R</i> )- BnBoPhoz	<b>1a</b>	10	33	25 (S)
12	[Rh(COD) <sub>2</sub> ]OTf/( <i>R</i> )-Spiro- P	<b>1a</b>	<5	<5	<5
13	[Rh(COD) <sub>2</sub> ]OTf/( <i>R</i> )-H8- BINAM-P	<b>1a</b>	30	64	<5
14	[Rh(COD) <sub>2</sub> ]OTf/( <i>S</i> )- PhanePhos	<b>1a</b>	>99	>99	<5
15	[Rh(COD) <sub>2</sub> ]OTf/( <i>R</i> )-Xyl- PhanePhos	<b>1a</b>	>99	>99	<5

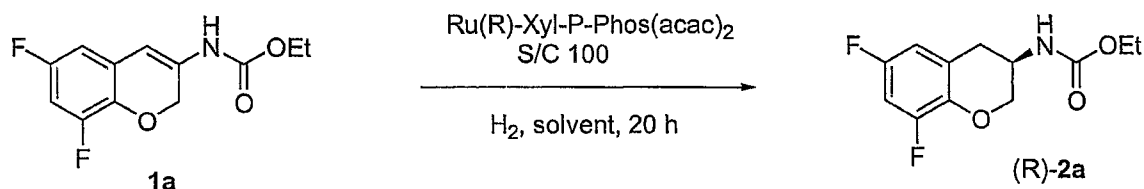
a) Reaction conditions: 0.3mmol substrate, 0.003mmol catalyst (or 0.003 rhodium precursor, 0.0036mmol ligand stirred in 1mL MeOH at r.t. for 0.5hrs(S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD column, 70% MeOH:30% IPA, 5 0.5mL/min.

### ***Solvent, temperature, and pressure optimisation***

The reaction shown in Scheme 3 was studied in order to determine the influence of solvent, temperature, and pressure in the Ru(*R*)-Xyl-P-Phos(acac)<sub>2</sub>-catalysed asymmetric hydrogenation of **1a**.

The study showed that, at S/C 100 (Table 6), MeOH is the solvent of choice, giving the highest enantioselectivity (Table 6, entries 1-11). Moreover, temperature and pressure experiments in MeOH showed that the activity was both temperature dependent (Table 6, entries 1, 12 and 15) and pressure dependent at low temperatures (Table 6, entries 15 and 16 (low T) vs. entries 1 and 17 (higher T)). Notably, the enantioselectivity of the reaction is neither temperature nor pressure dependent (Table 6, entries 1, 15 and 17).

## Scheme 3



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**Table 6.** Influence of Solvent, Temperature, and Pressure in the Ru(R)-Xyl-P-Phos(acac)<sub>2</sub>-catalysed Asymmetric Hydrogenation of 1a.<sup>a</sup>

Entry	Solvent	T(°C)	P(bar)	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup> (210nm)
1	MeOH	60	30	>99	>99	90(R)
2	EtOH	60	30	88	97	82(R)
3	iPrOH	60	30	21	70	78(R)
4	1-PrOH	60	30	50	90	76(R)
5	1-BuOH	60	30	32	70	71(R)
6	2-BuOH	60	30	20	47	66 (R)
7	CF <sub>3</sub> CH <sub>2</sub> OH	60	30	>99	>99	56 (R)
8	DCM	60	30	>99	>99	71 (R)
9	DCE	60	30	65	88	64 (R)
10	THF	60	30	<5	<10	-
11	Tol	60	30	>99	>99	76 (R)
12	MeOH	30	30	<5	<10	-
13	DCM	30	30	17	54	72 (R)
14	MeOH/DCM 1/1	30	30	11	40	88 (R)
15	MeOH	40	30	71	92	90 (R)
16	MeOH	40	10	<5	13	-
17	MeOH	60	10	>99	>99	90 (R)

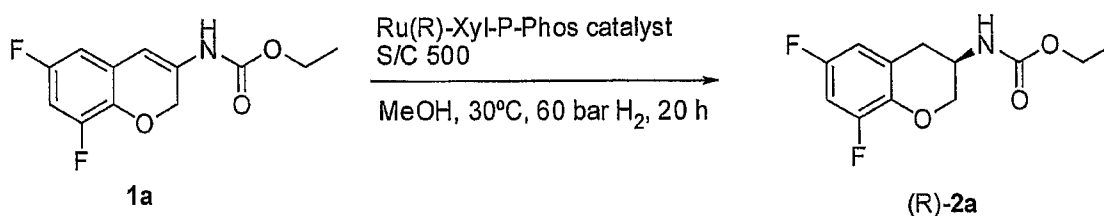
a) Reaction conditions: 0.3mmol 1a, 0.003mmol catalyst (S/C=100/1), 3mL solvent, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

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### Concentration optimisation

Concentration optimisation experiments in the Ru-catalysed asymmetric hydrogenation (see Scheme 4 below) were performed at substrate to catalyst ratio of 500/1. As shown in Table 7, moderate conversion was obtained at S/C 500 and 0.5M substrate concentration and in the presence of Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> (entry 1).

**Scheme 4**



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**Table 7.** Concentration Optimisation in the Ru-catalysed Asymmetric Hydrogenation of 1a.<sup>a</sup>

Entry	Catalyst	[S] (mmol/mL)	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup> (210nm)
1	Ru( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	0.5	21	60	92( <i>R</i> )
2	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	0.5	13	42	92( <i>R</i> )
3	Ru( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	1	9	36	91( <i>R</i> )
4	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	1	10	17	88( <i>R</i> )

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a) Reaction conditions: 0.3mmol 1a, S/C=500/1, MeOH, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

5 **Substrate purity**

Substrate 1a of higher purity than that used in the [(bisphosphine)RuLX<sub>2</sub>] catalysis experiment (see Table 1) was tested in the asymmetric hydrogenation using a series of Ru-bisphosphine based catalysts (Table 8).

10 Generally, in the case of ruthenium-dmf adducts a similar behaviour to the previous batch was observed (Table 8, entries 1 and 3 vs. Table 1, entries 1 and 4). A slightly higher e.e was observed in the case of Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> (Table 8, entries 8 and 9 vs. Table 1, entry 12). The activity of Ru-arene based catalysts was higher when purer material was used (Table 8, entry 5 vs. Table 3a, entry 7, Table 8, entry 6 vs. Table 1, entry 9). [RuCl(*R*-Tol-BINAP)(*p*-cymene)]Cl showed not only an  
15 increased activity, but also improved enantioselectivity (Table 8, entry 7 vs. Table 1, entry 10), while Ru(*S*-P-Phos)(acac)<sub>2</sub> catalyst led to no conversion to the hydrogenated product (Table 8, entry 10 vs. Table 1, entry 13).

20 **Table 8.** Asymmetric hydrogenation of **1a** using Ru-bisphosphine-based catalysts.<sup>a</sup>

Entry	Catalyst	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup>
1	RuCl <sub>2</sub> -( <i>R</i> )-P-Phos-(dmf) <sub>2</sub>	91	98	79( <i>R</i> )
2	RuCl <sub>2</sub> -( <i>R</i> )-MeBoPhoz-(dmf) <sub>2</sub>	<5	<5	-
3	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	>99	>99	84 ( <i>R</i> )
4	[RuCl( <i>S</i> )-P-Phos(benzene)]Cl	61	89	79 ( <i>S</i> )
5	[RuCl( <i>R</i> )-P-Phos( <i>p</i> -cym)]Cl	40	80	79 ( <i>R</i> )



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6	[RuCl( <i>R</i> )-Xyl-P-Phos( <i>p</i> -cym)]Cl	98	99	89( <i>R</i> )
7	[RuCl( <i>R</i> )-ToIBINAP( <i>p</i> -cym)]Cl	96	99	92 ( <i>R</i> )
8	Ru( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	93	99	92 ( <i>R</i> )
9	Ru( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	97	99	92 ( <i>R</i> )
10	Ru( <i>S</i> )-P-Phos(acac) <sub>2</sub>	<5	<5	-

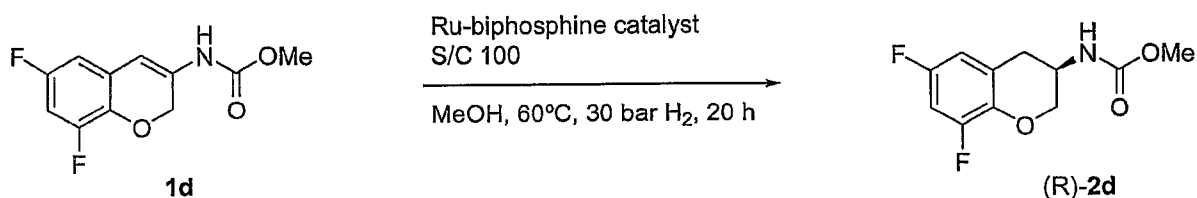
a) Reaction conditions: 0.3mmol 1a, 0.003mmol catalyst (S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

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### ***Methyl-substituted ene-carbamate***

The methyl-substituted ene-carbamate 1d was investigated in a similar Ru-bisphosphine catalyst screening. The racemate 2d was obtained via Pd/C-catalysed hydrogenation of 1d (Scheme 5 below).

**Scheme 5**



The results in Table 9 show that substrate 1d presents similar activity and enantioselectivity to substrate 1a. Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> showed no activity (Table 9, entry 9). Without wishing to be bound by theory, the catalyst behaviour could be strongly dependent on the type and level of impurities present in the material.

**Table 9.** Asymmetric hydrogenation of 1d using Ru-bisphosphine-based catalysts.<sup>a</sup>

Entry	Catalyst	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup>
1	10% Pd/C	98	>99	rac
2	RuCl <sub>2</sub> -( <i>R</i> )-P-Phos-(dmf) <sub>2</sub>	87	97	80( <i>R</i> )
3	RuCl <sub>2</sub> -( <i>R</i> )-MeBoPhoz-(dmf) <sub>2</sub>	<5	<5	-
4	RuCl <sub>2</sub> -( <i>R</i> )-Xyl-P-Phos-(dmf) <sub>2</sub>	>99	>99	85 ( <i>R</i> )
5	[RuCl( <i>S</i> )-P-Phos(benzene)]Cl	83	97	79 ( <i>S</i> )
6	[RuCl( <i>R</i> )-P-Phos( <i>p</i> -cym)]Cl	19	54	83 ( <i>R</i> )
7	[RuCl( <i>R</i> )-Xyl-P-Phos( <i>p</i> -cym)]Cl	99	99	84( <i>R</i> )
8	[RuCl( <i>R</i> )-TolBINAP( <i>p</i> -cym)]Cl	95	99	92 ( <i>R</i> )
9	Ru( <i>R</i> )-Xyl-P-Phos(acac) <sub>2</sub>	<5	<5	-
10	Ru( <i>S</i> )-P-Phos(acac) <sub>2</sub>	<5	<5	-

a) Reaction conditions: 0.3mmol 1d, 0.003mmol catalyst (S/C=100/1), 3mL MeOH, 60°C, 30bar H<sub>2</sub>, unoptimized reaction time 20hrs. b) e.e. and conversions were determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

5 Retention times: 1d, 10.6min (99.3% chemical purity at 254 nm, 96.3% chemical purity at 210nm); (*R*)-2d, 8.5 min; (*S*)-2d, 9.8 min.

***Influence of Acid Additives on the Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub>-catalysed hydrogenation of 1a and 1d***

10

The influence of acids on the Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub>-catalysed hydrogenation was investigated. It was observed (Table 10) that the fully hydrogenated product 2d

was obtained in the presence of Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> catalyst and different acids. Since the test reactions were run at high catalyst loadings, there was no differentiation from activity standpoint, while the enantioselectivity was not highly dependent on the type of acid used.

5

**Table 10.** Asymmetric hydrogenation of 1a and 1d using Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> and acid additives.<sup>a</sup>

Entry	Acid	Substrate	T(°C)	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup>
1	-	1a	60	97	99	92 ( <i>R</i> )
2	HBf <sub>4</sub> -Et <sub>2</sub> O	1a	60	>99	>99	93 ( <i>R</i> )
3	HCl, 1M in Et <sub>2</sub> O	1a	60	>99	>99	92 ( <i>R</i> )
4	HCl/H <sub>2</sub> O	1a	60	85	96 <sup>c</sup>	86 ( <i>R</i> )
5	HBr/H <sub>2</sub> O	1a	60	80	94 <sup>d</sup>	87 ( <i>R</i> )
6	CF <sub>3</sub> SO <sub>3</sub> H	1a	60	>99	>99	93 ( <i>R</i> )
7	CH <sub>3</sub> COOH	1a	60	>99	>99	92 ( <i>R</i> )
8	H <sub>3</sub> PO <sub>4</sub>	1a	60	>99	>99	93 ( <i>R</i> )
9	-	1d	60	<5	<5	-
10	H <sub>3</sub> PO <sub>4</sub>	1d	60	>99	>99	93 ( <i>R</i> )
11	H <sub>3</sub> PO <sub>4</sub>	1d	50	>99	>99	92 ( <i>R</i> )
12	HBf <sub>4</sub> -Et <sub>2</sub> O	1d	50	>99	>99	92 ( <i>R</i> )
13	HCl, 1M in Et <sub>2</sub> O	1d	50	93	98	87 ( <i>R</i> )
14	CF <sub>3</sub> SO <sub>3</sub> H	1d	50	>99	>99	92 ( <i>R</i> )
15	CH <sub>3</sub> COOH	1d	50	90	98	91( <i>R</i> )

a) Reaction conditions: 0.3mmol substrate, 0.003mmol catalyst, 0.03mmol acid  
10 (S/acid/C=100/25/1), 3mL MeOH, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e.  
was determined using Diacel ChiralPak AD-H column, 70% MeOH: 30% IPA,  
0.5mL/min. c) 48% byproduct. d) 52% byproduct

**Influence of Temperature**

The fact that the hydrogenation of 1a could be performed at lower temperatures (Table 11) in the presence of Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> catalyst and H<sub>3</sub>PO<sub>4</sub> as additive and the temperature independence of enantioselectivity indicated that lower catalyst loadings could be achievable. H<sub>3</sub>PO<sub>4</sub> was chosen to perform catalyst loading optimisation, with the substrate to acid ratio fixed at 4 to 1.

The asymmetric hydrogenation of both substrates was performed in high conversions at substrate to catalyst ratios of 1000/1 (Table 12). As seen in Table 12, substrate 1d is slightly more reactive than 1a. Without wishing to be bound by theory, it is thought that the slightly lower enantioselectivities observed in these experiments might be due to the increased acid to catalyst ratio.

**Table 11.** Influence of Temperature on the Asymmetric Hydrogenation of 1a.<sup>a</sup>

Entry	T (°C)	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup>
1	60	>99	>99	93 ( <i>R</i> )
3	50	>99	>99	93 ( <i>R</i> )
4	40	>99	>99	93 ( <i>R</i> )
5	30	>99	>99	93 ( <i>R</i> )

a) Reaction conditions: 0.3mmol substrate 1a, 0.003mmol catalyst, 0.03mmol acid (S/acid/C=100/25 /1), 3mL MeOH, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

**Table 12.** Reaction Conditions Optimisation in the Asymmetric Hydrogenation of 1a and 1d using Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub>.<sup>a</sup>

Entry	Subs -trate	S/C	H <sub>3</sub> PO <sub>4</sub> /C	T (°C)	[S] mmol/ mL	Conv (%) (254nm)	Conv (%) (210nm)	e.e. (%) <sup>b</sup>
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30

1	1a	100	25/1	60	0.1	>99	>99	93 (R)
2	1a	750	190/1	60	0.33	82	95	89 (R)
3	1a	1000	250/1	60	0.5	>99	>99	90 (R)
4	1a	1000	250/1	70	0.5	91	98	89 (R)
5	1d	100	25/1	60	0.1	>99	>99	93 (R)
6	1d	250	63/1	60	0.1	>99	>99	92 (R)
7	1d	500	125/1	60	0.2	>99	>99	89 (R)
8	1d	750	190/1	60	0.33	>99	>99	90 (R)
9	1d	1000	250/1	60	0.5	>99	>99	90 (R)
10	1d	1000	250/1	70	0.5	>99	>99	90 (R)

a) Reaction conditions: substrate, catalyst, (S/acid=4/1), 3mL MeOH, 30bar H<sub>2</sub>, unoptimised reaction time 20hrs. b) e.e. was determined using Diacel ChiralPak AD-H column, 70% MeOH:30% IPA, 0.5mL/min.

### ***Enantiopurity Upgrade***

5 The enantiopurity of the products may be further improved by recrystallisation.

For example, reaction mixtures that reached >98% conversion and >90% e.e. were combined, and tested for enantiopurity upgrade via recrystallisation. From one recrystallisation experiment, it was found that from DCM/Hexane, the enantiopurity of product (R)-2d could be upgraded from 91% e.e to 98.7% e.e. The yield of this  
 10 recrystallisation experiment was 70%. Evaporation of a MeOH solution of product 2a (approx. 91% e.e) led to a crystalline residue which was washed with DCM/Hexane = 1/25 mixture. The resulting product was recovered in 75% yield and 93% e.e, indicating the enantiopurity upgrade of product 2a.

15 The preferred reaction conditions can be described as follows: substrate 1d (methyl substituted ene-carbamate) was reduced to the desired product in >99% conversion and 90% e.e. in the presence of Ru(*R*-Xyl-P-Phos)(acac)<sub>2</sub> and H<sub>3</sub>PO<sub>4</sub> at substrate/acid/catalyst ratio of 1000/250/1, 0.5M substrate concentration in methanol, 60°C and 30 bar H<sub>2</sub> pressure. Importantly, the enantiopurity of the product resulting

from the catalytic step could be upgraded to 98.7% e.e. by an unoptimised recrystallisation from DCM/hexane.

**Experimental procedure for the synthesis of [(*R*)-Xyl-P-Phos RuCl<sub>2</sub> (dmf)<sub>2</sub>].**

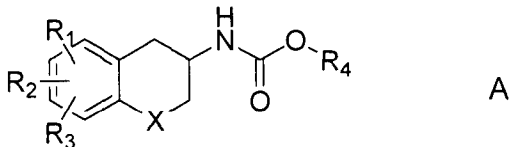
- 5 [Ru(benzene)Cl<sub>2</sub>]<sub>2</sub> (0.147mmol, 75 mg) and (*R*)-Xyl-P-Phos (0.32mmol, 242mg) were loaded in a 25mL Schlenk tube and tube evacuated by performing there vacuum/N<sub>2</sub> cycles. 2mL DMF was injected and the resulting mixture was stirred under N<sub>2</sub> at 105 °C for 2 h. The solvent was removed under high vacuum and the resulting brown solid was used in catalysis without further purification.

10

It will be appreciated that the invention may be modified within the scope of the appended claims.

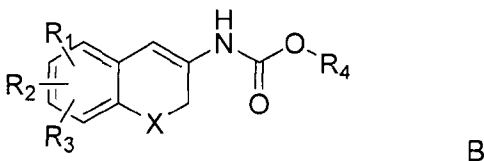
**WE CLAIM:**

1. A process for preparing an R or S enantiomer of a compound of formula A,



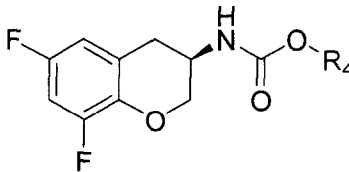
5

the process comprising subjecting a compound of formula B to asymmetric hydrogenation in the presence of a chiral catalyst and a source of hydrogen,



- 10 wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a  
15 phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

2. A process according to claim 1, wherein compound A has the following formula:



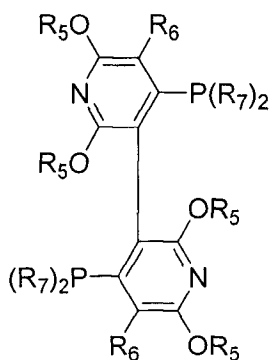
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3. A process according to claim 1 or claim 2, wherein R<sub>4</sub> is C<sub>1</sub> to C<sub>4</sub> alkyl.

4. A process according to claim 3, wherein R<sub>4</sub> is methyl, ethyl or <sup>t</sup>Bu.

25

5. A process according to claim 4, wherein R<sub>4</sub> is methyl.
6. A process according to claim 1, wherein R<sub>4</sub> is benzyl.
7. A process according to any one of claims 1 to 6, wherein the chiral catalyst comprises a transition metal complex comprising a chiral ligand.
8. A process according to claim 7, wherein the catalyst has the formula [(bisphosphine)Ru(arene)X']Y, [(bisphosphine)Ru(L)<sub>2</sub>] or [(bisphosphine)Ru(L')<sub>2</sub>X'<sub>2</sub>],  
 10 wherein the bisphosphine is chiral, X' is a singly-negative monodentate ligand, Y is a balancing anion, L is a doubly-negative bidentate ligand and L' is a non-ionic monodentate ligand.
9. A process according to claim 8, wherein the bisphosphine is the R or S  
 15 enantiomer of BINAP or TolBINAP.
10. A process according to claim 8, wherein the bisphosphine is the R or S enantiomer of a compound having the following formula

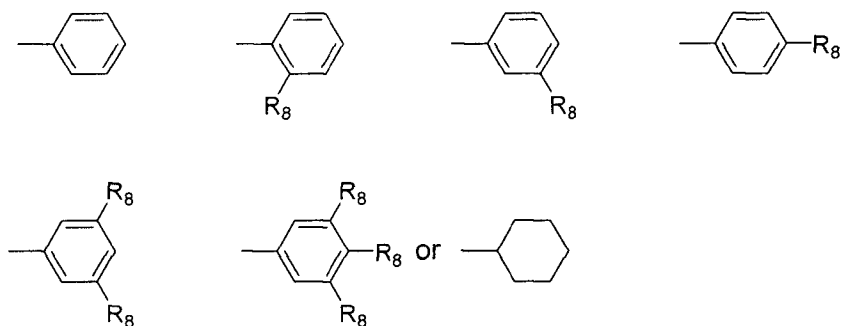


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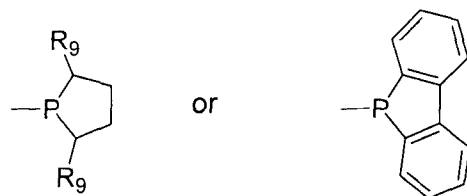
wherein R<sub>5</sub> is hydrogen or alkyl; R<sub>6</sub> is hydrogen, halogen, alkyl, alkoxy, hydroxy, chiral hydroxyalkyl, amino, mono- and di-alkylamino, vinyl or allyl; and R<sub>7</sub> is chosen from the following groups:



34



wherein  $R_8$  is alkyl, alkoxy or amino, and, where there is more than one group  $R_8$ , each  $R_8$  may be the same or different from the others; or the group  $P(R_7)_2$ , may form a group chosen from the following:

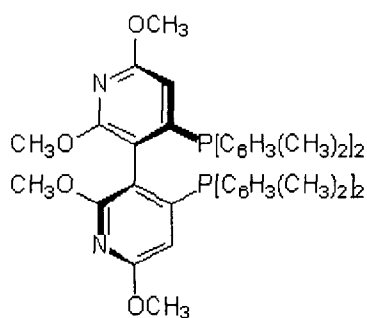


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wherein  $R_9$  is alkyl.

11. A process according to claim 10, wherein the bisphosphine is (S)- or (R)-PPhos.

10 12. A process according to claim 10, wherein the bisphosphine is (S)-(-)- or (R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine of the following formula



15

13. A process according to claim 12, wherein the bisphosphine is ((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine).

14. A process according to any one of claims 8 to 13, wherein at least one of X' and Y is chloride.
- 5 15. A process according to any one of claims 8 to 14, wherein arene is p-cymene or benzene.
16. A process according to any one of claims 8 to 13, wherein L is acac.
- 10 17. A process according to any one of claims 8 to 14, wherein L' is dmf.
18. A process according to claim 8, wherein the catalyst has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)Ru(acac)<sub>2</sub>].
- 15 19. A process according to claim 8, wherein the complex has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)RuCl<sub>2</sub>(dmf)<sub>2</sub>].
20. A process according to any one of claims 1 to 19, wherein the hydrogenation is carried out in the presence of an acid.
- 20 21. A process according to claim 20, wherein the acid is HBF<sub>4</sub>, HCl, HBr, CF<sub>3</sub>SO<sub>3</sub>H, CH<sub>3</sub>COOH or H<sub>3</sub>PO<sub>4</sub>.
22. A process according to claim 21, wherein the acid is H<sub>3</sub>PO<sub>4</sub>.
- 25 23. A process according to any one of claims 20 to 22, wherein the acid is present in a solvent.
24. A process according to claim 23, wherein the solvent is diethyl ether or water.
- 30 25. A process according to any one of claims 20 to 24, wherein the compound B/acid molar ratio ranges from 3.5/1 to 4/1.

26. A process according to claim 25, wherein the compound B/acid molar ratio ranges from 3.8/1 to 4/1.
27. A process according to claim 26, wherein the compound B/acid molar ratio  
5 ranges from 3.9/1 to 4/1.
28. A process according to claim 27, wherein the compound B/acid molar ratio is 4/1.
- 10 29. A process according to any one of claims 1 to 28, wherein the compound B/catalyst molar ratio ranges from 100/1 to 1000/1.
30. A process according to claim 29, wherein the compound B/catalyst molar ratio ranges from 250/1 to 1000/1.
- 15 31. A process according to claim 30, wherein the compound B/catalyst molar ratio ranges from 500/1 to 1000/1.
32. A process according to claim 31, wherein the compound B/catalyst molar ratio  
20 ranges from 750/1 to 1000/1.
33. A process according to claim 32, wherein the compound B/catalyst molar ratio is 1000/1.
- 25 34. A process according to any one of claims 1 to 33, wherein the hydrogenation is carried out in the presence of a solvent.
35. A process according to claim 34, wherein the solvent is selected from a substituted or unsubstituted straight- or branched-chain C<sub>1</sub> to C<sub>6</sub> alcohol, an arene or  
30 mixtures thereof.

36. A process according to claim 35, wherein the solvent is selected from MeOH, EtOH, iPrOH, 1-PrOH, 1-BuOH, 2-BuOH, CF<sub>3</sub>CH<sub>2</sub>OH, DCM, DCE, THF, toluene or a 1:1 mixture of MeOH and DCM.

5 37. A process according to any one of claims 1 to 36, wherein the hydrogenation is carried out at a temperature ranging from 30°C to 70°C.

38. A process according to claim 37, wherein the hydrogenation is carried out at a temperature ranging from 40°C to 60°C.

10

39. A process according to claim 38, wherein the hydrogenation is carried out at a temperature ranging from 50°C to 60°C.

40. A process according to claim 39, wherein the hydrogenation is carried out at a  
15 temperature of 60°C.

41. A process according to any one of claims 1 to 40, wherein the hydrogenation is carried out at a pressure ranging from 10 bars to 30 bars.

20 42. A process according to claim 41, wherein the hydrogenation is carried out at a pressure ranging from 20 bars to 30 bars.

43. A process according to any one of claims 1 to 42, wherein the hydrogenation is carried out at a pressure of 30 bars.

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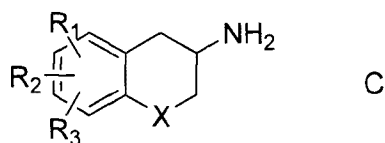
44. A process according to any one of claims 1 to 43, further comprising subsequently recrystallising the compound of formula A.

45. A process according to claim 44, wherein the recrystallisation is carried out in  
30 DCM/hexane.

46. A process according to any one of claims 1 to 45, wherein compound A is in the form of the S enantiomer.

47. A process according to any one of claims 1 to 45, wherein compound A is in the form of the R enantiomer.

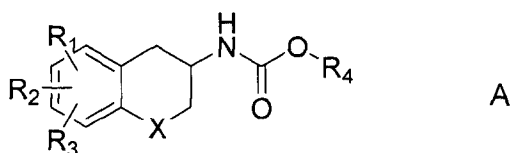
5 48. A process for preparing an R or S enantiomer of a compound of formula C,



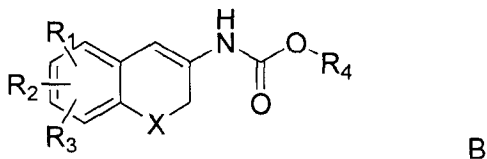
Comprising:

(i) forming an R or S enantiomer of a compound of formula A by a process according to any one of claims 1 to 47,

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the process for preparing the R or S enantiomer of a compound of formula A comprising subjecting a compound of formula B to asymmetric hydrogenation in the  
15 presence of a chiral catalyst and a source of hydrogen,

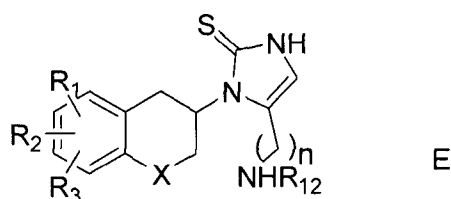


(ii) converting the R or S enantiomer of the compound A to the respective R or S enantiomer of a compound of formula C, wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the  
20 same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally  
25 substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

49. A process according to claim 48, wherein the compound A is converted to compound C by a reaction involving substituting the group  $-C(=O)-O-R_4$  with H.

5 50. A process according to claim 48, wherein the R or S enantiomer of compound A is converted to the respective R or S enantiomer of the compound of formula C by hydrolysis.

51. A process for forming an R or S enantiomer of the compound of formula E or a  
10 salt thereof:

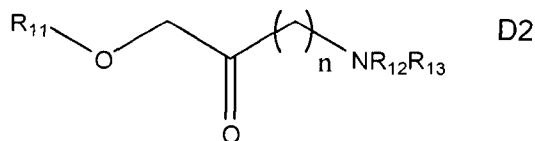


15 comprising forming the R or S enantiomer of a compound of formula C using the process as defined in claim 48, 49 or 50, and converting the R or S enantiomer of the compound of formula C to the R or S enantiomer of the compound of formula E, wherein: n is 1, 2 or 3 and  $R_{12}$  is hydrogen, alkyl or alkylaryl group.

20 52. A process according to claim 51, wherein the compound C is converted to the compound E by using the compound C as an amino component to build the N(1) moiety of the substituted imidazole-2-thione ring of compound E.

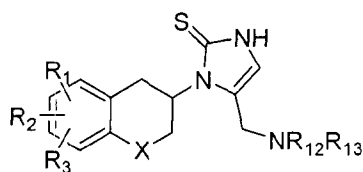
53. A process according to claim 51 or 52, wherein, the amino group on the  
25 compound C is converted to a 5-substituted imidazole-2-thione group, and the 5-substituted group is replaced with the group  $-(CH_2)_n-NHR_{12}$ , wherein: n is 1, 2 or 3 and  $R_{12}$  signifies hydrogen, alkyl or alkylaryl group.

54. A process according to claim 51 or 52, comprising reacting the R or S enantiomer of the compound of formula C with a compound of formula D2

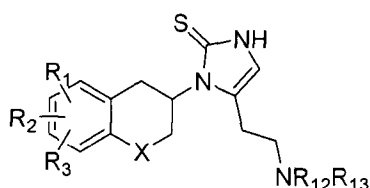


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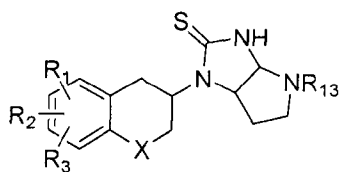
where n signifies 1, 2 or 3; when n is 1 or 2, R<sub>12</sub> signifies hydrogen, alkyl or alkylaryl group; R<sub>11</sub> signifies a hydroxyl protecting group and R<sub>13</sub> signifies an amino protecting group; when n signifies 3, R<sub>11</sub> signifies a hydroxyl protecting group but R<sub>12</sub> and R<sub>13</sub> taken together represent a phthalimido group; and with a water soluble thiocyanate salt in the presence of an organic acid in a substantially inert solvent, followed by subsequent deprotection of the intermediate products F to I:



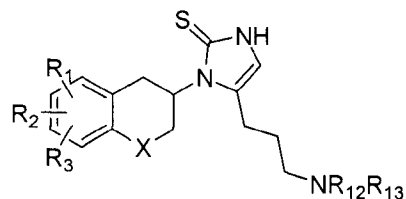
F



G



H



I

15

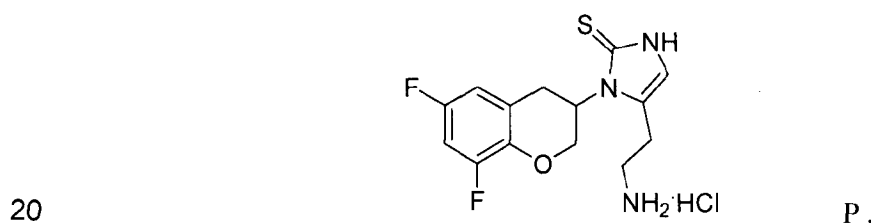
55. A process according to any one of claims 51 to 54, wherein  $n$  is 2 or 3.

56. A process according to any one of claims 51 to 54, wherein the compound E is  
(*R*)-5-(2-aminoethyl)-1-(6-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;

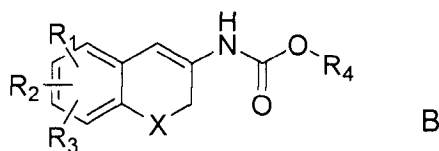
- 5 (*R*)-5-(2-aminoethyl)-1-(8-fluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*R*)-5-(2-aminoethyl)-1-(6,7-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*R*)-5-(2-aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*S*)-5-(2-aminoethyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*R*)-5-(2-aminoethyl)-1-(6,7,8-trifluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
10 (*R*)-5-aminomethyl-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*R*)-5-(3-aminopropyl)-1-(6,8-difluorochroman-3-yl)-1,3-dihydroimidazole-2-thione;  
(*R*)-1-(6,8-difluorochroman-3-yl)-5-(2-methylaminoethyl)-1,3-dihydroimidazole-2-thione,  
or a salt thereof.

15 57. A process according to claim 56, wherein the salt is the hydrochloride salt.

58. A process according to any one of claims 51 to 54, wherein the compound E is the respective *R* or *S* enantiomer of the compound of formula P:

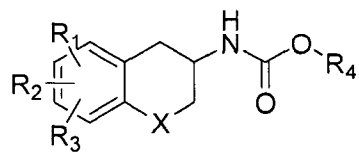


59. The use of a chiral catalyst comprising a transition metal complex which comprises a chiral ligand in the asymmetric hydrogenation of a compound of formula B,





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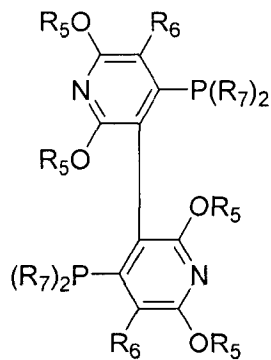


to prepare a compound of formula A , wherein X, R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub> and R<sub>4</sub> have the same meanings as defined in claim 1.

60. Use according to claim 59, wherein the catalyst has the formula  
 5 [(bisphosphine)Ru(arene)X']Y, [(bisphosphine)Ru(L)<sub>2</sub>] or [(bisphosphine)Ru(L')<sub>2</sub>X'<sub>2</sub>], wherein the bisphosphine is chiral, X' is a singly-negative monodentate ligand, Y is a balancing anion, L is a doubly-negative bidentate ligand and L' is a non-ionic monodentate ligand.

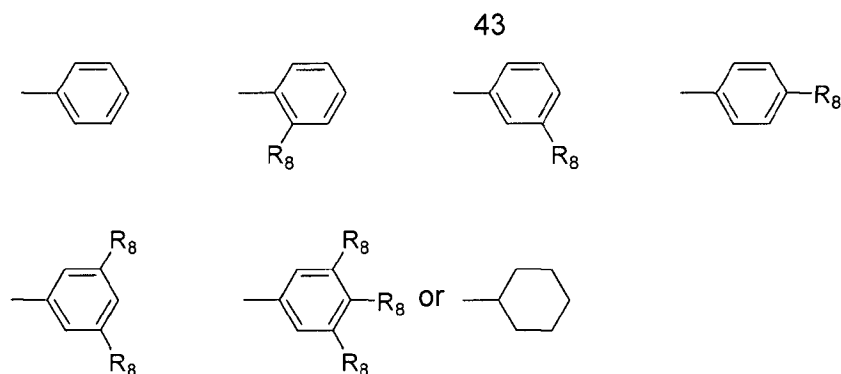
10 61. Use according to claim 60, wherein the bisphosphine is the R or S enantiomer of BINAP or TolBINAP.

62. Use according to claim 60, wherein the bisphosphine is the R or S enantiomer of a compound having the following formula

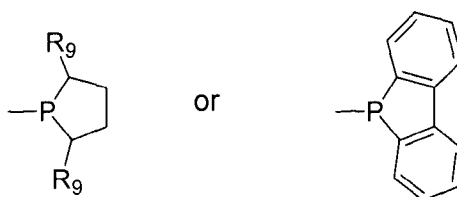


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wherein R<sub>5</sub> is hydrogen or alkyl; R<sub>6</sub> is hydrogen, halogen, alkyl, alkoxy, hydroxy, chiral hydroxyalkyl, amino, mono- and di-alkylamino, vinyl or allyl; and R<sub>7</sub> is chosen from the following groups:



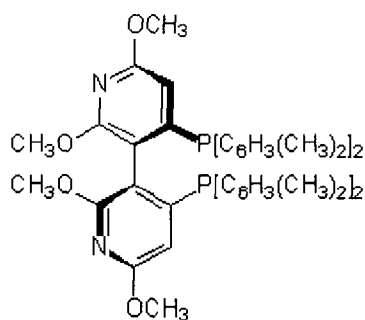
wherein  $R_8$  is alkyl, alkoxy or amino, and, where there is more than one group  $R_8$ , each  $R_8$  may be the same or different from the others; or the group  $P(R_7)_2$ , may form a group  
5 chosen from the following:



wherein  $R_9$  is alkyl.

10 63. Use according to claim 60, wherein the bisphosphine is (S)- or (R)-PPhos.

64. Use according to claim 60, wherein the bisphosphine is (S)-(-)- or (R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine of the following formula



65. Use according to claim 64, wherein the bisphosphine is (R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine.

66. Use according to any one of claims 60 to 65, wherein at least one of X' and Y is  
5 chloride.

67. Use according to any one of claims 60 to 66, wherein arene is p-cymene or benzene.

68. Use according to any one of claims 60 to 65, wherein L is acac.

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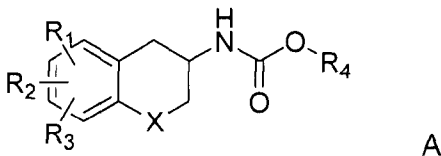
69. Use according to any one of claims 60 to 66, wherein L' is dmf.

70. Use according to claim 59 or 60, wherein the complex has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)Ru(acac)<sub>2</sub>].

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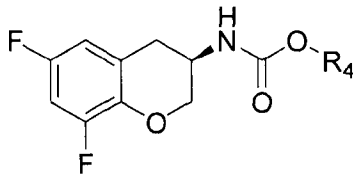
71. Use according to claim 59 or 60, wherein the complex has the formula [((R)-(+)-2,2',6,6'-tetramethoxy-4,4'-bis(di(3,5-xylyl)phosphino)-3,3'-bipyridine)RuCl<sub>2</sub>(dmf)<sub>2</sub>].

72. Compound of formula A, the compound being in the form of the  $\geq 95$  % pure R  
20 enantiomer, or the  $\geq 95$  % pure S enantiomer,



wherein wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify  
hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or  
25 dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon  
chains, straight or branched, containing from one to six carbon atoms, optionally  
substituted by aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the  
term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen  
or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and  
30 wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

73. A compound according to claim 72, wherein compound A has the following formula:



5 74. A compound according to claim 72 or claim 73, wherein R<sub>4</sub> is C<sub>1</sub> to C<sub>4</sub> alkyl.

75. A compound according to claim 74, wherein R<sub>4</sub> is methyl, ethyl or <sup>t</sup>Bu.

76. A compound according to claim 75, wherein R<sub>4</sub> is methyl.

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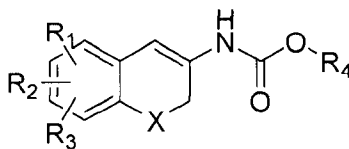
77. A compound according to claim 72 or 73, wherein R<sub>4</sub> is benzyl.

78. A compound according to any one of claims 72 to 77, wherein the compound is in the form of the R enantiomer.

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79. A compound according to claim 72, wherein the compound is in the form of the S enantiomer.

80. Compound of formula B



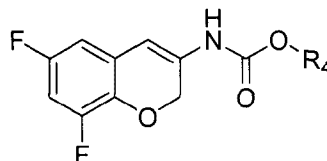
B

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wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group; and R<sub>4</sub> is alkyl or aryl, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by  
25 aryl, alkoxy, halogen, alkoxycarbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl group, optionally substituted by alkyloxy, halogen or nitro group; and

the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

81. A compound according to claim 80, wherein compound B has the formula:



5

wherein R<sub>4</sub> is alkyl or aryl.

82. A compound according to claim 80 or 81, wherein R<sub>4</sub> is C<sub>1</sub> to C<sub>4</sub> alkyl.

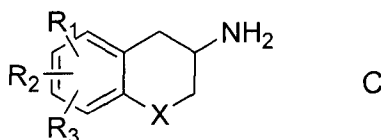
10 83. A compound according to claim 82, wherein R<sub>4</sub> is methyl, ethyl or <sup>t</sup>Bu.

84. A compound according to claim 83, wherein R<sub>4</sub> is methyl.

85. A compound according to claim 80 or 81, wherein R<sub>4</sub> is benzyl.

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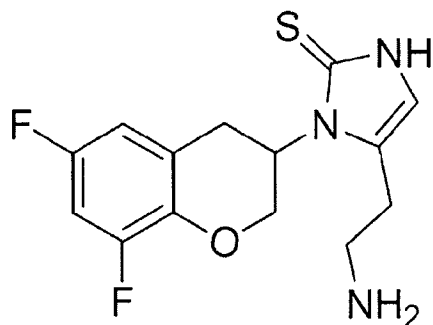
86. L-tartrate salt of an R or S enantiomer of a compound of formula C



C

20 wherein: X is oxygen; R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> are the same or different and signify hydrogen, halogen, alkyl, alkyloxy, hydroxy, nitro, alkylcarbonylamino, alkylamino or dialkylamino group, wherein: the term alkyl means hydrocarbon chains, straight or branched, containing from one to six carbon atoms, optionally substituted by aryl, alkoxy, halogen, alkoxy carbonyl or hydroxycarbonyl groups; the term aryl means a phenyl or naphthyl  
25 group, optionally substituted by alkyloxy, halogen or nitro group; and the term halogen means fluorine, chlorine, bromine or iodine, and wherein at least one of R<sub>1</sub>, R<sub>2</sub> and R<sub>3</sub> is fluorine.

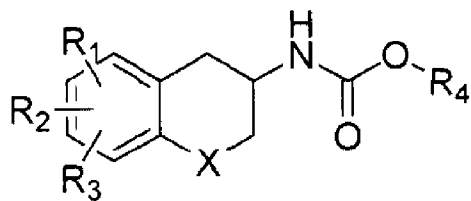
87. A compound produced by the process of any one of claims 51 to 54, the compound being an R or S enantiomer of the compound of formula P, or a salt thereof



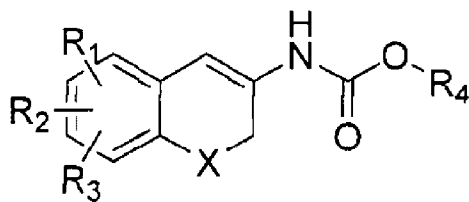
P

wherein the compound of formula P is an R or S enantiomer with an enantiomeric  
5 purity of at least 95%.

88. A compound according to claim 87, wherein the salt is the hydrochloride salt.



A



B